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Development and applications of position-sensitive solid-state gamma ray detectors

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Abstract

The development of high-resolution position-sensitive, solid-state detectors will enable gamma ray detectors with improved sensitivity and imaging capabilities. The gamma ray astrophysics group at NRL has been developing germanium strip detectors for several years. We have shown that three-dimensional locations for gamma ray interactions can be determined with sub-millimeter accuracy, and have also demonstrated imaging capability within a single germanium strip detector. We have also initiated work on thick, silicon strip detectors. This was based on the fact that three sequential interactions can enable the energy and direction cone of the incident gamma ray to be determined, even without total energy deposition of the incident gamma ray. We are also working on low-power ASICs that are required to handle the large number of channels associated with arrays of strip detectors. Progress on this work will be presented, along with applications to high-energy astrophysics, medical imaging, nuclear physics, detection of fissile materials, and monitoring of environmental radioactivity.

Keywords: Gamma-ray imaging; gamma-ray spectroscopy; position-sensitive detectors; gamma ray astrophysics; nuclear medicine; Compton imaging.

1. Introduction

There is a clear need for gamma ray detectors with improved sensitivity and/or imaging in a number of fields. These include the diverse areas of gamma ray astronomy, homeland security, nuclear physics, environmental clean-up of nuclear waste, and nuclear medicine. One approach to meeting these

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requirements is to use position-sensitive solid-state detectors that combine excellent energy resolution and excellent position resolution. There are several options that can be considered including orthogonal strip planar detectors, highly segmented co-axial detectors, and pixel detectors. These devices make high-resolution gamma ray imaging practical for the first time. At NRL, we initiated development of planar orthogonal-strip germanium detectors about ten years ago for specific applications in gamma ray astronomy. For a next generation Compton telescope, the combination of improved energy and angular resolution promises dramatic improvement in sensitivity relative to earlier instruments. Substantial progress has been made on the development of these detectors. This includes measurements of general performance characteristics, development of alternate contact technology, demonstration of 3D position readout, and demonstration of Compton imaging with multiple detectors as well as within a single detector.

As discussed in Section 3, both the energy and direction of an incident gamma ray can be determined without absorbing the full energy if the gamma ray undergoes two Compton scatter interactions followed by a third interaction. Since only Compton interactions are required, this multiple Compton technique enables low-Z materials such as silicon to be considered in the construction of large, high-efficiency imaging detectors.

We present our work with germanium detectors in Section 2. In Section 3, the triple Compton technique and some of its performance characteristics are discussed. In Section 4, the development of thick silicon strip detectors that are enabled by the 3-Compton technique is described. In Section 5 we discuss the development of ASICs that will facilitate the implementation of large area and large volume solid-state Compton imagers. Several applications for this gamma ray imaging technology are discussed in Section 6.

2. Germanium Strip Detectors

We first tested a germanium orthogonal strip detector in the early 1990's [1]. This device was 45 mm x 45 mm x 10 mm thick and was fabricated by Eurisys Mesures using diffused-Li n-type contacts and boron–implanted p-type contacts. It had a 5 x 5 array of strips with ?9 mm pitch (see Figure 1). This detector was used to investigate the resolution performance and response across the strips [2]. Based on the good performance obtained, we procured a second device, but with a 25 x 25 array of 2 mm strips. This device has been used extensively to further characterize the performance of germanium strip detectors. We have used this detector to demonstrate the capability to measure the depth of gamma ray interactions to ?0.5 mm from the relative arrival times of the electrons and holes at the opposing anodes [3-5]. We have demonstrated Compton imaging with multiple detectors [6], and have also demonstrated Compton imaging from two interactions within a single detector [7] as shown in Figure 2.

In collaboration with LBNL an orthogonal strip device, similar to those above but using amorphous germanium as the contact technology, has been fabricated [8]. This contact technology has advantages in fabrication and is also not limited in strip pitch as are Li contacts (due to lithium diffusion). We are also pursuing the development of larger devices. A detector with amorphous germanium (amGe) contacts, 80 mm x 80 mm x 20 mm thick with 1.25 mm strip pitch, is currently under fabrication.

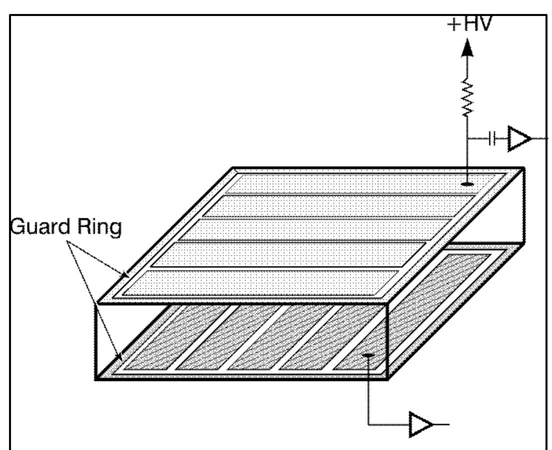

Figure 1. Schematic of a double-sided orthogonal strip detector.

3. Three Compton Scatter Technique

The energy and direction of an incident gamma ray can be determined if the gamma ray undergoes two Compton scatters followed by a third interaction [9]. Although this possiblity has not been generally known, it was suggested as a technique for consideration in a nuclear medical application of Compton imaging [10]. Use of this technique enables large, high-efficiency detectors over a broad range ef energies.

Consider a gamma ray, E_1, incident on a detector array that has good position resolution and good energy resolution. We further suppose this gamma ray undergoes two successive Compton scatter interactions followed by a third interaction as shown in Figure 3, where E_1, E_2, and E_3 are the incident photon energies for each interaction. The energy losses (to the recoil electrons) are L_1, L_2, and L_3, and the Compton scatter angles at the first two interaction sites are θ_1, θ_2. The Compton formula for the second interaction is:

$$\cos\theta_2 = 1 - m_e c^2 \left(\frac{1}{E_3} - \frac{1}{E_2} \right) \qquad (1)$$

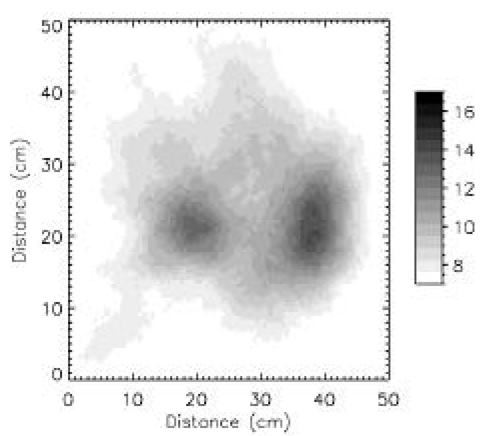

Figure 2. Image of a ^{137}Cs source and a ^{22}Na source obtained with a single germanium strip detector. For details see Ref. [7].

and the energy losses at the first two interaction sites are:

$$L_1 = E_1 - E_2 \qquad (2)$$

$$L_2 = E_2 - E_3 \qquad (3)$$

Solving equation (3) for E_3 and substituting into (1) yields and equation with E_2 as the only unknown, since θ_2 is determined from the locations of the three interactions. Thus the energy E_2 is given by:

$$E_2 = \frac{L_2}{2} + \frac{1}{2}\left[L_2^2 + \frac{4 m_e c^2 L_2}{1 - \cos\theta_2} \right]^{\frac{1}{2}} \qquad (4)$$

where $m_e c^2$ is the rest mass of the electron. The incident gamma ray energy, E_1 is then determined from (2). The direction cone of the incoming gamma ray can be determined just as for a conventional Compton telescope. The uncertainties in the energy and direction cone of the incident gamma ray are given in [9], and are functions of the detector's energy and position resolutions.

The standard Compton formula used above assumes the scattering takes place with a free electron at rest. Taking into account the pre-interaction momenta of bound electrons introduces additional uncertainties in the energy and angle of the scattered

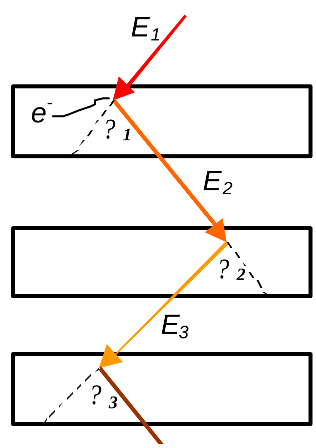

Figure 3. The 3-Compton scatter technique.

gamma ray [11] [12]. This phenomenon is often referred to as Doppler broadening. The additional uncertainties on the energy resolution and angular resolution are especially pronounced at low gamma ray energies. The relative uncertainties become smaller for higher energy gamma rays and for lower-Z materials [13]. For 511 keV gamma rays undergoing Compton scattering in germanium, the angular uncertainty is typically about 1 degree.

Figure 4 shows the uncertainties in the angular resolution for a 750 keV gamma ray incident on a Compton imager that is assumed to have 2 keV energy resolution, and 3-D position resolution of 0.5 mm. Three components of the angular error as a function of scattering angle at the first interaction site are due to the errors in the locations of the interaction sites (geometric), the errors due to the uncertainty in the energy determination, and the error due to Doppler broadening. The geometric error is determined by the assumed 0.5 mm interaction uncertainties at the three interaction locations (in this example we have assumed the path length is the mean free path length for the appropriate gamma ray energy in a silicon detector array with a 20% fill factor). The angular error due to energy resolution becomes large for forward scatters where the angular errors due to geometry result in large uncertainties in the incident gamma ray energies that in turn, are reflected in large errors in the scattering angle at the first interaction site. For backscattered gamma rays (scatter angle close to 180?), the energy of the scattered gamma ray varies slowly with scatter angle (approaching $m_e c^2/2$) with a correspondingly small error in the uncertainty of the incident gamma ray and the associated error in the scattering angle. The Doppler broadening error is relatively unimportant for small scatter angles, but becomes significant for scatter angles above about 120?. The net result is that events with scatter angles between about 20? and 120? are those best utilized for Compton imaging. Fortunately, the Compton cross section has a broad peak in the region of interest from several hundred keV to several MeV.

The energy resolution in the triple Compton mode is degraded from that obtained with full absorption in a single germanium detector and is also non-gaussian. Figure 5 shows a simulation of the expected energy distribution for 1 MeV gamma rays incident on a large silicon Compton telescope. The full-width-half-maximum (FWHM) is about 10 keV, with about 50% of the events within the FWHM. It should be noted that some fraction of the events would be fully absorbed. For these, the energy resolution can be significantly better, being determined by the RMS sum of the errors at the individual energy loss locations.

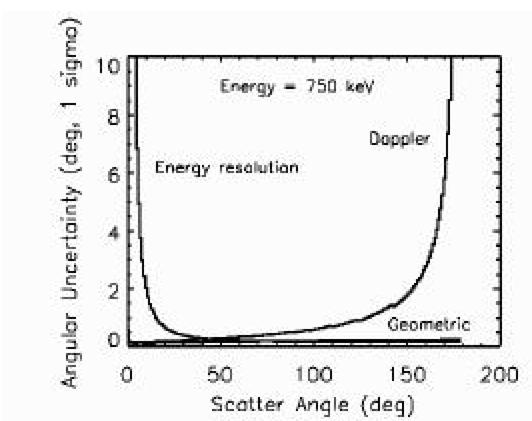

Figure 4. Angular uncertainties in Compton scattering due to Doppler broadening, detector energy resolution (2 keV) and detector position resolution (0.5 mm) for 750 keV incident gamma rays in silicon.

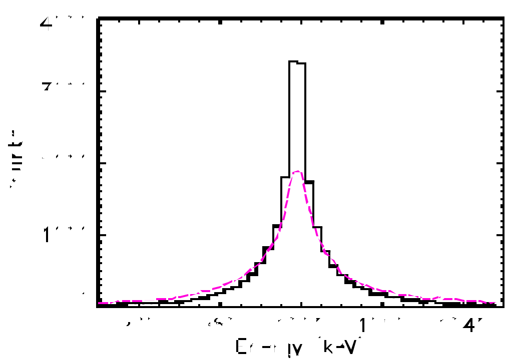

Figure 5. Simulated energy resolution for a 1 MeV gamma ray beam on a silicon detector array. The solid curve assumes perfect energy and position resolution and the dotted curve assumes 2 keV energy and 2 mm position resolution.

There are also situations of practical interest where the performance can be improved somewhat. These include:

Known source location: If the location of a presumed source is known (e.g. the location of a supernovae or novae in the astrophysical context) then separate energies of the incident gamma ray can be determined using the Compton scatter formula at both the first and second interaction sites. Thus two independent determinations of the incident energy are made. The average of these two will generally provide a better estimation for the energy of the incident gamma ray.

Small Compton scatter angle, $?_2$: If a small scatter angle at the second interaction site results in a large energy uncertainty for E_1 as discussed above (see Fig 4), a better energy estimate for E_1 may still be determined by analysis of Compton scattering at the third interaction site, and adding the energy losses L_1 and L_2 to the estimated energy E_3.

Known source energy: If the energy of the source gamma ray is known then the known energy can be substituted for the estimated energy from the triple Compton reconstruction, and the known energy can be used to provide the best estimate of the scatter angle and direction cone for the incoming gamma ray. This will be applicable to Compton imaging in nuclear medicine, for example, where the energies of the gamma rays are known.

4. Silicon Strip Detectors

Because the three-Compton techniques relies only on Compton scattering, it is possible to consider low-Z detectors for gamma ray applications. Therefore, we have initiated development of orthogonal silicon-strip detectors for these applications. Silicon has several advantages when compared to germanium. First, the devices should give good performance at temperatures much higher than that required for germanium. This may become very important for large devices, especially for instruments to be flown in space. Second, the Doppler broadening effect will not degrade the energy and angular resolution as severely as with higher-Z materials [11] [12]. Finally, there may be advantages derived from the large infrastructure for silicon wafer processing associated with the semiconductor industry.

We are pursuing several alternatives for thick silicon detectors. Ideally, thick detectors with 3-D position sensitivity are desired. However, intrinsic silicon detectors cannot be fabricated in devices thicker than about 1.5 to 2 mm. The energy resolution performance of small planar devices with an area of approx. 0.2 cm^2 and 2 mm thick have been measured at temperatures from –60 C to room temperature [14]. An energy resolution of 1.1 keV was obtained at – 60 ?C and 1.9 keV at 0 ?C for 60 keV gamma rays. Encouraged by this performance, we are pursuing the fabrication of large area (57 mm x 57 mm active area, 2 mm thick) intrinsic silicon strip detectors with 0.89 mm pitch manufactured by SINTEF Electronics and Cybernetics (Norway), and expect to test several units this year.

Thicker devices are desired in order to reduce the electronics channel count. This requires the use of lithium-drifted devices. Planar devices with thickness of 10mm or more have been fabricated in the past. We are undertaking the development of thick, orthogonal Si(Li) strip detectors in collaboration with LBNL. Alternative contact technologies are being developed that are more compatible with the segmented contact requirement. This work is reported in another paper at this conference [15]. Progress to date includes the demonstration of boron-implanted p-type contacts and amorphous silicon (amSi) n-type contacts that show ?2 keV energy resolution at -40 C. This performance is also achieved with initial devices incorporating test strips. The goal is to fabricate and test 50 mm x 50 mm x 6-mm thick orthogonal strip detectors (2 mm pitch) in the next several months.

Protic et al. [16] have developed an alternate approach to fabricating thick Si(Li) strip detectors. They use plasma etch technology to fabricate narrow gaps in both boron-implanted and diffused-Li contacts. They have shown excellent charge collection and modest energy resolution at room temperature. They are fabricating several devices that we will use to measure their performance characteristics vs. temperature. Initial results show 2-

3 keV energy resolution at – 40 ?C for 60 keV gamma rays from ^{241}Am.

For space applications, there is also a concern about the long-term performance of solid-state detectors in the ionizing radiation environment associated with cosmic rays and the trapped radiation belts. Several 6 mm thick Si(Li) planar detectors were tested for radiation damage effects using a 200 MeV proton beam at the Indiana University Cyclotron Facility [17]. No degradation of the energy resolution was observed for a proton flux of 8.7 x 10^8 protons/cm^2, which is typical of the total dose expected in a several year mission at low altitude. Very modest radiation damage effects were observed with a dose of 8.7 x 10^9 protons/cm^2, but this damage was annealed at 60 ?C. Therefore, Si(Li) detectors appear to be quite resistant to damage from the radiation environment expected for gamma ray astronomy experiments.

5. ASICs

The large quantity of solid-state strip detectors required for many applications will require the development of Application Specific Integrated Circuits (ASICs). The requirements are to maintain good energy resolution (typically 2 keV) and also to achieve adequate timing resolution to implement the 3-D position resolution described in Section 2. We are pursuing two independent developments to meet these goals. The first is a modified version of the IDE AS VAT-TAT chip set in collaboration with the Univ. of Michigan. Our modified ASIC should provide a dynamic range of >100, energy range 10-1500 keV, energy resolution of 2.5 keV, and time resolution of 20 ns. The estimated power will be about 4 mW/channel.

Indigo Systems Corp. (Goleta, CA) will investigate another ASIC design under funding through an SBIR. This effort will explore the use of an analog pipeline memory to characterize the pulse shapes induced on each strip. This technique will serve two purposes. The pulse shapes can be analyzed to implement a fast timing discriminator function, which in turn could be used to time the relative arrival times of the electrons and holes on opposite planar surfaces to determine the position of the energy loss in the third dimension. In addition, the induced pulses on adjacent “spectator” strips can be used as a vernier to improve the x and y positions to a fraction of the strip pitch [3]. If successful, this would provide the position resolution required for a specific application, but with a larger strip pitch and an associated reduction in the channel count and power requirements.

6. Applications

6.1. Astrophysics

A high resolution Compton telescope has been identified as the preferred instrument for the next low-energy gamma ray astronomy mission for several reasons. It has a very large field-of-view and associated multiplex advantage. Relative to coded aperture or collimated instruments the efficiency, and hence sensitivity, can be improved substantially with this instrument configuration. The efficiency of the COMPTEL instrument on NASA’s Compton Gamma Ray Observatory (CGRO), the first Compton imaging instrument to fly in space, was typically 1% or less. An Advanced Compton Telescope (ACT) has been proposed that would use large arrays of position-sensitive solid-state detectors in a high efficiency configuration. The use of position-sensitive detectors with excellent spectral resolution also reduces the error in the width of the Compton scatter angle dramatically, thereby providing direct improvement of about a factor of 10 relative to COMPTEL for a similar size instrument.

Finally, a key to improved sensitivity is rejection of internal background. COMPTEL used time-of-flight to provide good rejection of instrumental background, but it was still the limiting factor in sensitivity. Time-of-flight is not possible with the high-efficiency, compact designs under development or investigation. However, other techniques, using the electron direction of motion and/or background re-construction of events have potential for excellent background rejection. The latter depends critically on the energy and position resolution achieved in the detectors.

6.2. Nuclear Physics

Nuclear physics experiments have increasing requirements for improved position resolution and energy resolution in particle-nucleus interactions that result in a large multiplicity of reaction products. For example, the GRETA collaboration is exploring alternative detector technologies that would provide excellent energy and position resolution so that tracking algorithms could be used to unfold the reaction products. One approach being investigated is the use of highly segmented germanium coaxial detectors. In this case the induced signals on the many segments from the interactions of one or more gamma rays must be unfolded to reconstruct the incoming events. An alternative being considered is the use of orthogonal strip detectors discussed here. One disadvantage of strip detectors is the requirement for guard rings to reduce the surface currents and associated noise, and the associated 'dead' material. Development of solid-state devices that do not require guard rings would be very advantageous.

6.3. Special Nuclear Materials

Terrorist activities in recent years have elevated the importance of surveillance and detection of nuclear materials, including the covert transport of nuclear weapons. The Defense Threat Reduction Agency (DTRA), for example, has been tasked with developing perimeter surveillance and detection for special nuclear materials at several military installations. The low gamma-ray and neutron emissivities of ^{235}U and ^{239}Pu make this a difficult task. One obvious approach is to construct much larger detectors using conventional scintillation materials. Alternatively, gamma ray and neutron detectors that can implement improved sensitivity through imaging or background reduction using some of the concepts discussed here may have advantages.

6.4. Nuclear Medicine

Several groups have investigated Compton imaging as an alternative to Single Photon Emission Computed Tomography (SPECT) for nuclear medical applications [18] [19]. A significant advantage might be gained by eliminating the collimator used in SPECT that absorbs over 99.9% of the gamma rays. Two major difficulties with Compton imaging must be addressed. One is the relatively low efficiency of most Compton implementations. The other is the severe degradation in angular resolution due to the Doppler broadening effect described in Section 3. This is especially constraining for low energy gamma rays such as the 140 keV radiation from ^{99m}Tc that is used in the majority of SPECT applications. A significant improvement relative to single photon Compton imaging can be realized, in principle, with coincident Compton imaging [20]. Improved imaging with reduced dose could be achieved if the location of every decay could be determined uniquely. This is possible with the use of selected radionuclides that emit a three-gamma cascade or positron-decay isotopes that are accompanied by a coincident gamma ray. ^{94}Tc and ^{14}O are respective examples. Liang et al. [21] proposed this technique, and compared the relative capabilities of SPECT and their triple gamma coincidence tomographic imaging concept. Hart [22] was granted a patent for this concept.

Consider first the case of a positron-decay nuclide with the emission of a coincident gamma ray. ^{14}O is an example. The two 511 keV gamma rays will interact in the position-sensitive detector array in a standard PET mode. The locations of the 511 keV interactions define a pencil beam along which the decay occurred. The third gamma ray (2.312 MeV for ^{14}O) Compton scatters in the detector array at a first interaction site, and the scattered gamma ray interacts by Compton scattering or photoelectric effect at a second interaction site. A Compton direction cone for the latter event will intersect the PET pencil beam at one, or perhaps two locations in the region of interest. Thus, the origin of the decay is determined to a point rather than a line. The relatively high energy of the 2.312 MeV ^{14}O gamma ray will result in a lower Compton scatter efficiency, but the angular uncertainty in the Compton scatter angle due to Doppler broadening associated with this gamma ray will be small.

Similarly, for three coincident gamma rays emitted in a cascade, each of the gamma rays can be restricted to a direction cone. The intersection of the three direction cones defines a limited number of regions where the decay may have occurred--

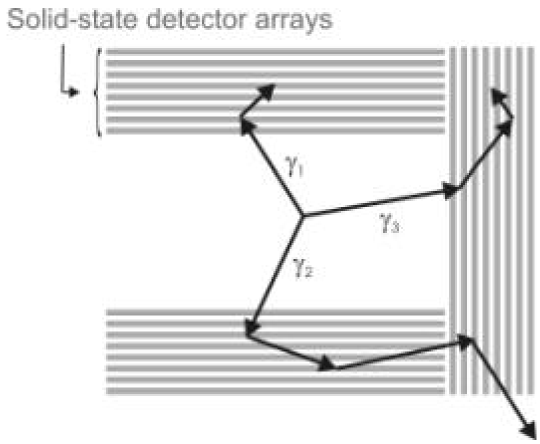

Figure 6. Coincident Compton imager for nuclear medicine using 3-gamma cascade.

typically only one in the region of interest. Several suitable radioisotopes have decays with a cascade of three of more gamma rays. ^{94}Tc app ears to be a particularly attractive choice due to its three high-energy gamma rays at 702, 850 and 871 keV that are emitted in 100% of the decays. The low Doppler broadening associated with these high-energy gamma rays, the half-life of 293 minutes, and the wide range of radiopharmaceuticals that have been developed for ^{99m}Tc.

Shown in Fig. 6 is a detector configuration that consists of many layers of 3-D position-sensitive detectors. A large solid angle, greater than 3? ster, and multiple layers of detectors are used to maximize the probability for detection of each of the gamma rays. Use of low-Z detectors (Si, Ge) is preferred to ensure high probability for the first event to be a Compton-scatter interaction. Ideally the second interaction would be a photoelectric event, but this requires a high-Z detector. Full energy absorption for each gamma ray would enable clear energy identification of each incident gamma ray, providing an unambiguous position from the intersection of the three Compton direction cone.

A Monte Carlo simulation has been run to show the capability for imaging a 3-dimensional object using the coincident Compton image technique. The simulation assumed ^{94}Tc uniformly distributed in five cubic volumes: a 4 mm x 4 mm x 4 mm central cube, with four 2 mm x 2 mm x 2 mm cubes located on four of the eight corners of the central cube. ^{94}Tc coincident gamma rays were detected by a first detector array located at distances of 5 cm, 10 cm, 20 cm, or 30 cm from the center of the distribution. The scattered gamma rays were detected by a second detector array separated by about 10 cm from the first detector. The central region encompassing the radioactive regions was divided into 1 mm^3 voxels, and each voxel was tested for consistency with the conical shell for each of the three gamma rays. Those voxels consistent with all three Compton cones are treated as a valid location for the radioactive decay. The uncertainty in the Compton scatter angle included Doppler broadening at the first interaction s ite and the energy and position resolutions of the detectors. This process was repeated for a significant number of radioactive decays, producing a summed distribution of possible source regions. Surface maps of the regions are shown in Fig. 7 for source to first detector distances

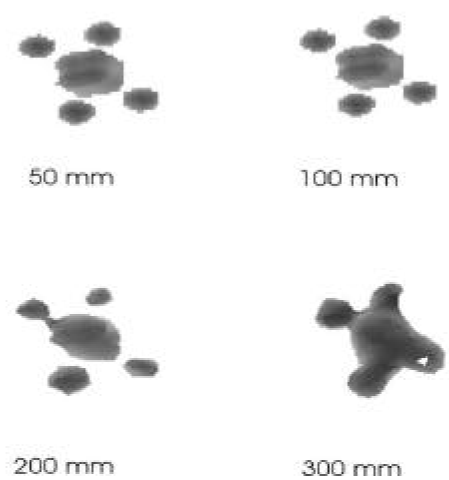

Figure 7. Simulation of a coincident Compton imager using ^{94}Tc. The source is a 4 mm cube with 4 2 mm cubes attached at the corners. The distances shown are the distance from the source to the first interaction site.

of 5 cm, 10 cm, 20 cm and 30 cm. It is seen that, with this simplified simulation, an image resolution of ?2 mm is realized for a source to first interaction distance of up to 20 cm, consistent with that expected based on the limitations of Doppler broadening at these gamma ray energies.

7. Summary

Position-sensitive detectors using solid-state detectors promise significant improvements in sensitivity and imaging capabilities for future gamma ray applications. We have demonstrated many important capabilities using orthogonal strip germanium detectors. The multiple Compton scatter technique should enable high efficiency and high sensitivity instruments for several applications. It also enables the use of low-Z detectors. We are pursuing several options for orthogonal strip germanium and silicon detectors to meet several of these applications.

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References

[1] P. Wallyn, C. Chapuis, Ph. Durouchoux, D. Gutknecht, and J. Poulalion, “Position Sensitive High Resolution Spectrometer”, *Proc SPIE* vol. 1344, pp. 53-65 , 1990.

[2] S. E. Inderhees, B. F. Phlips, R. A. Kroeger, W. N. Johnson, R L. Kinzer, J. D. Kurfess, B. Graham, and N. Gehrels, “Spectroscopy, imaging and Compton-scatter polarimetry with a germanium strip detector”, IEEE Trans Nucl Sci. vol. 43, pp. 1467 – 1471, 1996.

[3] M. Momayesi, W. K Warburton, and R. A. Kroeger, "Position resolution in a ge-strip detector", *Proc SPIE* vol. 3768, pp. 530-537, 1999.

[4] M. Amman and P N. Luke; "Three-dimensional position sensing and field shaping in orthogonal-strip germanium gamma-ray detectors", *Nucl. Instrum Methods Phys Res* A, vol. 452, pp. 155-166, 2000.

[5] E. A. Wulf, W. N. Johnson. R. A. Kroeger, J. D. Kurfess, B. F. Phlips, and J. Ampe, "Three dimensional readout system for germanium strip detectors", this conference, 2002

[6] B. F. Phlips, S. E. Inderhees, R. A. Kroeger, W. N. Johnson, R. L. Kinzer, J. D. Kurfess, B. L. Graham,and N. Gehrels, ” Performance of a compton telescope using position-sensitive germanium detectors”, IEEE Trans Nucl Sci. 43 (3): 1472-1475 Part 2, 1996.

[7] E. A. Wulf, J. Ampe, W. N. Johnson, R. A. Kroeger, J. D. Kurfess and B. F. Phlips, “Depth Measurement in a Strip Detector”, 2001 IEEE Nuclear Sciences Symposium Conf. Record, 2002.

[8] P.N. Luke, M. Amman, B.F. Phlips, W.N. Johnson, R.A. Kroeger, “Germanium orthogonal strip detectors with amorphous-semiconductor contacts”, IEEE Trans Nucl Sci. vol. 47, pp. 1360 –1363, 2000.

[9] J. D. Kurfess, W. N. Johnson, R. A. Kroeger, and B. F. Phlips, "Considerations for the Next Compton Telescope Mission " *AIP Conf. Proc.* vol. 510, pp. 789-793, 2000.

[10] N. Dogan and D. K. Wehe, "Optimization and angular resolution calculations for a multiple compton scatter camera", *1993 IEEE Nucl. Sci. Symp. and Med. Imaging Conf. Record*, pp.269-273, 1994.

[11] C. E. Ordonez, A. Bolozdynya, and W. Chang, "Doppler broadening of energy spectra in Compton cameras", 1997 *IEEE Nucl Sci*. Symp. vol. 2, pp. 1361-1365, 1998.

[12] C. E. Ordonez, A. Bolozdynya, and W. Chang "Dependence of Angular Uncertainties on the Energy Resolution of Compton Cameras", *IEEE Nucl. Sci. Symp.* , vol. 2, pp. 1122-1125, 1998.

[13] Y. F. Du, Z. He, G. F. Knoll, D. K. Wehe, and W. Li "Evaluation of a Compton scattering camera using 3-D position sensitive CdZnTe detectors", Proc. *SPIE,* vol. 3768, pp.228-238, 1999.

[14] B .F. Phlips, W. N. Jophnson, R. A. Kroeger, and J. D. Kurfess “Development of Thick Intrinsic Silicon Detectors for Hard X-ray and Gamma –ray Detection” 2001 IEEE Nuclear Sciences Symposium Conf. Record, paper N12-12, 2002.

[15] C. Tindall, I. D. Hau, and P. N. Luke, “Evaluation of Si(Li) Detectors for Use in Compton Telescopes”, this conference, 2002.

[16] D. Protic, T. Krings, and R. Schleichert “Development of Double-sided Microstructured Si(Li)-Detectors 2001 IEEE Nuclear Sciences Symposium Conf. Record, paper R16-2, 2002.

[17] Ethan L. Hull, Richard H. Pehl, Craig Tindall, Paul N. Luke, James D. Kurfess, ”Radiation damage and charge collection in Si(Li) gamma-ray detectors”, to be submitted Nucl. Instr. & Meth.

[18] J. W. LeBlanc et al., "Experimental results from the C-SPRINT prototype Compton camera", *IEEE Tran. Nucl. Sci*., vol. 46, no. 3, pp. 201-204, 1999.

[19] A. Bolozdynya, W. Chang, and C. E. Ordonez, "A concept of a cylindrical Compton camera for SPECT", *1997 IEEE Nucl. Sci. Symp.* vol. 2, pp. 1047-1051, 1998.
[20] J. D. Kurfess and B. F. Phlips "Coincident Compton Nuclear Medical Imager" 2001 IEEE Nuclear Sciences Symposium Conf. Record, paper M4-5 (2002).
[21] Z. Liang, H. Hart, and A. Schoenfeld, "Triple coincidence tomographic imaging without image processing", *IEEE Conf. on Engineering in Medicine and Biology*, pp. 825-826, 1987
[22] H. Hart, U.S. Patent No. 4,833,327 "High-Resolution Radioisotopic Imaging System", 1989.